

# Measurement of the Time-Dependent $CP$ Asymmetry in $B^0 \rightarrow D_{CP}^{(*)} h^0$ Decays

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We report a measurement of the time-dependent  $CP$ -asymmetry parameters  $\mathcal{S}$  and  $\mathcal{C}$  in color-suppressed  $B^0 \rightarrow D^{(*)0} h^0$  decays, where  $h^0$  is a  $\pi^0$ ,  $\eta$ , or  $\omega$  meson, and the decays to one of the  $CP$  eigenstates  $K^+ K^-$ ,  $K_S^0 \pi^0$ , or  $K_S^0 \omega$ . The data sample consists of  $383 \times 10^6$   $Y(4S) \rightarrow B\bar{B}$  decays collected with the BABAR detector at the PEP-II asymmetric-energy  $B$  factory at SLAC. The results are

$S = -0.56 \pm 0.23 \pm 0.05$  and  $C = -0.23 \pm 0.16 \pm 0.04$ , where the first error is statistical and the second is systematic.

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Measurements of time-dependent  $CP$  asymmetries in  $B^0$  meson decays, through the interference between decays with and without  $B^0$ – $\bar{B}^0$  mixing, have provided stringent tests on the mechanism of  $CP$  violation in the standard model (SM). The time-dependent  $CP$  asymmetry amplitude  $\sin 2\beta$  has been measured with high precision in the  $b \rightarrow c\bar{c}s$  decay modes [1], where  $\beta = -\arg(V_{cd}V_{cb}^*/V_{td}V_{tb}^*)$  is a phase in the Cabibbo-Kobayashi-Maskawa (CKM) quark-mixing matrix [2].

In this Letter, we present a measurement of the time-dependent  $CP$  asymmetry in  $B^0$  meson decays to a neutral  $D$  meson and a light neutral meson through a  $b \rightarrow c\bar{u}d$  color-suppressed tree amplitude. Interference between decay amplitudes with and without  $B^0$ – $\bar{B}^0$  mixing contribution occurs if the neutral  $D$  meson decays to a  $CP$  eigenstate. The measured time-dependent asymmetry is expected to be different from  $\sin 2\beta$  measured in the charmonium modes due to the subleading amplitude  $b \rightarrow u\bar{c}d$ , which has a different weak phase. This amplitude is suppressed by  $V_{ub}V_{cd}^*/V_{cb}V_{ud}^* \approx 0.02$  relative to the leading diagram. Therefore, the deviation is expected to be small in the SM [3,4].

Many other decay modes that have significant contribution from loop diagrams have been studied [5] to constrain or discover new physics due to unobserved heavy particles in the loop diagrams in  $B$  decays. This kind of new physics would not affect the decays presented in this Letter because only tree diagrams contribute to these modes. However,  $R$ -parity-violating ( $\tilde{R}_p$ ) supersymmetric processes [3,7] could enter at tree level in these decays, leading to a deviation from the SM prediction.

The analysis uses a data sample of  $348 \text{ fb}^{-1}$ , which corresponds to  $(383 \pm 4) \times 10^6 Y(4S)$  decays into  $B\bar{B}$  pairs collected with the BABAR detector at the asymmetric-energy  $e^+e^-$  PEP-II collider. The BABAR detector is described in detail elsewhere [8]. We use the GEANT4 simulation toolkit [9] to simulate interactions of particles traversing the BABAR detector and to take into account the varying detector conditions and beam backgrounds.

We fully reconstruct  $B^0$  mesons [10] decaying into a  $CP$  eigenstate in the following channels:  $D^{(*)0}\pi^0$  ( $D^0 \rightarrow K^+K^-$ ,  $K_S^0\omega$ ) [11],  $D^{(*)0}\eta$  ( $D^0 \rightarrow K^+K^-$ ) with  $D^{*0} \rightarrow D^0\pi^0$ , and  $D^0\omega$  ( $D^0 \rightarrow K^+K^-$ ,  $K_S^0\omega$ ,  $K_S^0\pi^0$ ). From the remaining particles in the event, the vertex of the other  $B$  meson,  $B_{\text{tag}}$ , is reconstructed, and its flavor is identified (tagged). The proper decay time difference  $\Delta t = t_{CP} - t_{\text{tag}}$  between the signal  $B$  ( $t_{CP}$ ) and  $B_{\text{tag}}$  ( $t_{\text{tag}}$ ) is determined from the measured distance between the two  $B$  decay vertices projected onto the boost axis and the boost ( $\beta\gamma =$

0.56) of the center-of-mass (c.m.) system. The  $\Delta t$  distribution is given by

$$F_{\pm}(\Delta t) = \frac{e^{-|\Delta t|/\tau}}{4\tau} \{1 \mp \Delta w \pm (1 - 2w) \times [\eta_f \sin(\Delta m \Delta t) - C \cos(\Delta m \Delta t)]\}, \quad (1)$$

where the upper (lower) sign is for events with  $B_{\text{tag}}$  being identified as a  $B^0$  ( $\bar{B}^0$ ),  $\eta_f$  is the  $CP$  eigenvalue of the final state,  $\Delta m$  is the  $B^0$ – $\bar{B}^0$  mixing frequency,  $\tau$  is the mean lifetime of the neutral  $B$  meson, the mistag parameter  $w$  is the probability of incorrectly identifying the flavor of  $B_{\text{tag}}$ , and  $\Delta w$  is the difference of  $w$  for  $B^0$  and  $\bar{B}^0$ . The neural-network based tagging algorithm [12] has six mutually exclusive categories and a measured total effective tagging efficiency of  $(30.4 \pm 0.3)\%$ . Neglecting CKM-suppressed decay amplitudes, we expect the  $CP$  violating parameters  $S = -\sin 2\beta$  and  $C = 0$  in the SM.

The event selection criteria are determined by maximizing the expected signal significance based on the simulation of signal and generic decays of  $B\bar{B}$  and  $e^+e^- \rightarrow q\bar{q}$  ( $q = u, d, s, c$ ) continuum events. The selection requirements vary by mode due to different signal yields and background levels.

A pair of energy clusters in the electromagnetic calorimeter (EMC), isolated from any charged tracks and with a lateral shower shape consistent with photons, is considered as a  $\pi^0$  candidate if both cluster energy deposits exceed 30 MeV and the invariant mass of the pair is between 100 and 160 MeV/ $c^2$ . Charged tracks are considered as pions, except for those used in  $D^0 \rightarrow K^+K^-$  reconstruction, where the kaons must be consistent with the kaon hypothesis [13]. We reconstruct  $\eta$  mesons in  $\gamma\gamma$  and  $\pi^+\pi^-\pi^0$  modes. Each photon is required to have an energy exceeding 100 MeV and, when combined with any other photon in the event, to not have an invariant mass within 5 MeV/ $c^2$  of the  $\pi^0$  nominal mass [14]. The invariant mass is required to be within approximately 30 MeV/ $c^2$  (8 MeV/ $c^2$ ) of the  $\eta$  nominal mass for  $\eta \rightarrow \gamma\gamma$  ( $\eta \rightarrow \pi^+\pi^-\pi^0$ ). Both  $\pi^0$  and  $\eta \rightarrow \gamma\gamma$  candidates are kinematically fitted with their invariant masses constrained at their respective nominal values. The  $\omega \rightarrow \pi^+\pi^-\pi^0$  candidates are accepted if the invariant mass is within approximately 22 MeV/ $c^2$  of the nominal  $\omega$  mass, depending on the  $D^0$  decay mode. The  $K_S^0 \rightarrow \pi^+\pi^-$  candidates are required to have an invariant mass within 10 MeV/ $c^2$  of the  $K_S^0$  nominal mass and  $\chi^2$  probability of forming a common vertex greater than 0.1%. The distance between the  $K_S^0$  decay vertex and the primary interaction point projected on the plane perpendicular to the



beam axis is required to be greater than twice its measurement uncertainty.

The vector meson  $\omega$  is fully polarized in  $D^0 \rightarrow K_S^0 \omega$  decays. Two angular distributions of the  $\omega$  decay are used to discriminate against background: (a)  $\cos\theta_N^D$ , defined in the  $\omega$  rest frame, the cosine of the angle between the  $D^0$  direction and the normal to the decay plane of  $\omega \rightarrow \pi^+ \pi^- \pi^0$ , and (b)  $\cos\theta_D^D$ , the cosine of the angle between the direction of one pion in the rest frame of the remaining pion pair and the direction of the pion pair. The signals are distributed according to  $\cos^2\theta_N^D$  and  $1 - \cos^2\theta_D^D$ , while the background distributions are nearly uniform. We require  $|\cos\theta_N^D| > 0.4$  and  $|\cos\theta_D^D| < 0.9$ .

For the  $D^0$  in  $D^{*0} \rightarrow D^0 \pi^0$ , the invariant mass of the  $D^0$  candidate is required to be within 30 MeV/ $c^2$  of the world-average  $D^0$  mass. For the  $D^0$  in  $B^0 \rightarrow D^0 h^0$ , the invariant mass window is tightened, ranging from  $\pm 14$  to  $\pm 29$  MeV/ $c^2$ , depending on the mode. In both cases, the  $D^0$  is kinematically fitted with its mass constrained at its nominal value. The invariant mass difference between  $D^{*0}$  and  $D^0$  candidates is required to be within  $\pm 2.7$  MeV/ $c^2$  of the nominal value. For  $B^0 \rightarrow D^{*0} \pi^0$  with  $D^0 \rightarrow K_S^0 \omega$ , we require  $|\cos\theta_H^*| > 0.4$ , where  $\theta_H^*$  is the angle between the momenta of the  $B^0$  and the  $\pi^0$  from the  $D^{*0}$  in the  $D^{*0}$  rest frame.

The signal is characterized by the kinematic variables  $m_{\text{ES}} = \sqrt{(s/2 + \mathbf{p}_0 \cdot \mathbf{p}_B)^2/E_0^2 - \mathbf{p}_B^2}$  and  $\Delta E = E_B^* - E_{\text{beam}}^*$ , where the asterisk denotes the values evaluated in the c.m. frame, the subscripts 0, beam, and  $B$  denote the  $e^+e^-$  system, the beam, and the  $B$  candidate, respectively, and  $\sqrt{s}$  is the c.m. energy. We require  $m_{\text{ES}} > 5.23$  GeV/ $c^2$ . The  $\Delta E$  distribution for signal events is asymmetric and varies by decay mode. Depending on the mode, the lower (upper) boundary of the  $\Delta E$  selection window varies from  $-95$  to  $-35$  MeV ( $+35$  to  $+85$  MeV). The reconstructed  $|\Delta t|$ , and its uncertainty  $\sigma_{\Delta t}$  are required to satisfy  $|\Delta t| < 15$  ps and  $\sigma_{\Delta t} < 2.5$  ps.

The background from continuum  $q\bar{q}$  production is suppressed based on the event topology. In the c.m. frame, the  $B$  mesons are produced nearly at rest and decay isotropically, while the quarks in the process  $e^+e^- \rightarrow q\bar{q}$  are produced with large relative momentum and result in a jetlike topology. The ratio of the second to zeroth order Fox-Wolfram moments [15], determined from all charged tracks and clusters in the EMC with energy greater than 30 MeV, must be less than 0.5. The  $q\bar{q}$  background is further suppressed by a Fisher discriminant  $\mathcal{F}$  [16], constructed with the following variables, evaluated in the c.m. frame: (a)  $L_2/L_0$  where  $L_i = \sum_j p_j^* |\cos\theta_j^*|^i$ , summed over the remaining particles in the event after removing the daughter particles from the  $B^0$ ,  $p_j^*$  is the momentum of particle  $j$ , and  $\theta_j^*$  is the angle of the momentum with respect to the  $B^0$  thrust axis [17]; (b)  $|\cos\theta_T^*|$ , where  $\theta_T^*$  is the angle between the  $B^0$  thrust axis and the thrust axis of

the rest of the event; (c)  $|\cos^2\theta_B^*|$ , where  $\theta_B^*$  is the angle between the beam direction and the direction of the  $B^0$ ; (d) total event thrust magnitude; and (e) total event sphericity [18].

For  $B^0 \rightarrow D^0 \omega$  decays, we add two angular variables to  $\mathcal{F}$ :  $\cos\theta_N^B$  and  $\cos\theta_D^B$ , analogous to  $\cos\theta_N^D$  and  $\cos\theta_D^D$  in  $D^0 \rightarrow K_S^0 \omega$ . The signal distributions for the  $B^0$  system are the same as those in the  $D^0$  system. The background distributions are close to  $2 - \cos^2\theta_N^B$  and uniform in  $\cos\theta_D^B$ . The requirement on  $\mathcal{F}$  depends on the background level in each mode; the signal selection (background rejection) efficiency is 60%–86% (72%–94%).

Within each reconstructed decay chain, the fraction of events that have more than one candidate ranges from less than 1% to about 10%, depending on the mode. We select one candidate with the most signal-like Fisher discriminant value for each mode. A total of 1128 events are selected, of which 751 are tagged (the absolute value of the flavor-tagging neural-network output greater than 10% of the maximum).

The signal and background yields are determined by a fit to the  $m_{\text{ES}}$  distribution using a Gaussian distribution for the signal peak and a threshold function [19] for the combinatorial background. We obtain  $340 \pm 32$  signal events ( $259 \pm 27$  tagged). The contribution from each mode is shown in Table I, and the  $m_{\text{ES}}$  distributions are shown in Fig. 1. We investigate potential backgrounds that might peak in the  $m_{\text{ES}}$  signal region by studying data in the  $D^0$  mass sideband (outside a window of  $\pm 3$  standard deviations of the mass peak) and simulated  $e^+e^- \rightarrow B\bar{B}$  events. We estimate that  $(0.8 \pm 2.6)\%$  of the  $CP$ -even signal yield and  $(5.4 \pm 2.2)\%$  of the  $CP$ -odd signal yield are background, based on the simulation. Approximately half of the peaking background found in simulation is from  $B^- \rightarrow D^0 \rho^- (\rightarrow \pi^0 \pi^-)$  with a low momentum  $\pi^-$ . Other sources include  $B^0 \rightarrow \pi^+ \pi^- \pi^0$  and  $B^0 \rightarrow D^{*0} h^0$ , with  $D^0$  decaying to a flavor eigenstate, e.g.,  $K^- \pi^+$ . We find that the peaking background from the  $D^0$  mass sideband data in

TABLE I. Signal yields. Uncertainties are statistical only. The  $CP$  parity of the  $D^0$  is indicated in the column of  $D_{CP}$ . The combined value is from a simultaneous fit to all modes.

$\eta_f = +1$ ( $CP$ even)			$\eta_f = -1$ ( $CP$ odd)		
Mode	$D_{CP}$	$N_{\text{signal}}$	Mode	$D_{CP}$	$N_{\text{signal}}$
$D_{K_S^0 \omega}^0 \pi^0$	—	$26.2 \pm 6.3$	$D_{KK}^0 \pi^0$	+	$104 \pm 17$
$D_{K_S^0 \pi^0}^0 \omega$	—	$40.0 \pm 8.0$	$D_{KK}^0 \eta_{\gamma\gamma}$	+	$28.9 \pm 6.5$
$D_{K_S^0 \omega}^0 \omega$	—	$23.2 \pm 6.8$	$D_{KK}^0 \eta_{3\pi}$	+	$14.2 \pm 4.7$
$D_{KK}^{*0} \pi^0$	+	$23.2 \pm 6.3$	$D_{KK}^0 \omega$	+	$51.2 \pm 8.5$
$D_{KK}^{*0} \eta_{\gamma\gamma}$	+	$9.8 \pm 3.5$	$D_{K_S^0}^{*0} \pi^0$	—	$5.5 \pm 3.3$
$D_{KK}^{*0} \eta_{3\pi}$	+	$6.8 \pm 2.9$			
Combined		$131 \pm 16$			$209 \pm 23$
Total		$340 \pm 32$			

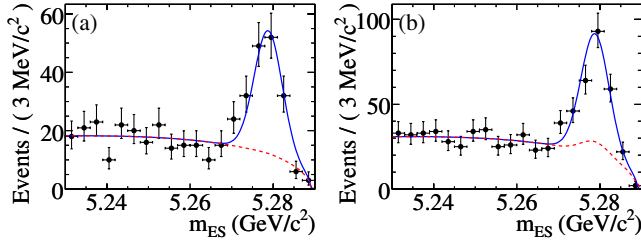


FIG. 1 (color online). The  $m_{\text{ES}}$  distributions with a fit to (a) the  $CP$ -even and (b) the  $CP$ -odd modes combined in the data. The solid curve represents the overall PDF projection, and the dashed curve represents the background.

$CP$ -even modes is consistent with the simulation. For  $CP$ -odd modes, we find a larger peaking component in  $D^0$  sideband data than expected from simulation. Therefore, we increase the estimated total peaking background fraction for  $CP$ -odd events to  $(11 \pm 6)\%$  to account for the excess found in the  $D^0$  sideband data. We estimate that 65% of the peaking background arises from charmless decays with potentially large  $CP$ -violating asymmetries. We account for this possibility in the systematic uncertainty.

In order to extract  $CP$  violating parameters  $S$  and  $C$ , we fit the  $m_{\text{ES}}$  and  $\Delta t$  distributions of the 751 tagged events using a two-dimensional probability density function (PDF) that contains three components: signal, peaking background, and combinatorial background. The  $m_{\text{ES}}$  distribution is described in the previous paragraph. Its parameters are free in the fit. The peaking background is assumed to have the same  $m_{\text{ES}}$  shape as the signal. The signal decay-rate distribution shown in Eq. (1) accounts for dilution due to an incorrect assignment of the flavor of  $B_{\text{tag}}$  and is convolved with a sum of three Gaussian distributions, parameterizing the core, tail, and outlier parts of the  $\Delta t$  resolution function [13]. The widths and biases of the core and tail Gaussians are scaled by  $\sigma_{\Delta t}$ . The biases are nonzero to account for the charm meson flight from the  $B_{\text{tag}}$  vertex. The outlier Gaussian has a fixed mean (0 ps) and width (8 ps) to account for poorly-reconstructed decay vertices. The mistag parameters and the resolution function are determined from a large data control sample of  $B^0 \rightarrow D^{(*)-} h^+$  decays, where  $h^+$  is a  $\pi^+$ ,  $\rho^+$ , or  $a_1^+$  meson. The  $B^0$  lifetime and mixing frequency are taken from [6].

We use an exponential decay to model the  $\Delta t$  PDF of the peaking background. We account for possible  $CP$  asymmetries in the systematic uncertainty. The  $\Delta t$  PDF for combinatorial background consists of a term with zero lifetime to account for the  $q\bar{q}$  contribution, and an oscillatory term whose effective lifetime and oscillatory coefficients are free parameters in the fit to account for possible  $CP$  asymmetry in the background. The sum of a core Gaussian and an outlier Gaussian is sufficient to model the resolution function. The combinatorial background parameters are determined predominately by the events

in the  $m_{\text{ES}}$  sideband. The final PDF has 25 free parameters for fitting to all modes and tagging categories simultaneously.

We obtain  $S = -0.56 \pm 0.23 \pm 0.05$  and  $C = -0.23 \pm 0.16 \pm 0.04$ , where the first errors are statistical and the second are systematic. The statistical correlation between  $S$  and  $C$  is  $\rho = -2.4\%$ . The  $\Delta t$  distribution projections and the asymmetry ( $A = [N_{B^0\text{tag}}(\Delta t) - N_{\bar{B}^0\text{tag}}(\Delta t)] / [N_{B^0\text{tag}}(\Delta t) + N_{\bar{B}^0\text{tag}}(\Delta t)]$ ) for the events in the signal region are shown in Fig. 2. We check the consistency between  $CP$ -even and  $CP$ -odd modes by fitting them separately and find (statistical errors only)  $S_{\text{even}} = -0.17 \pm 0.37$ ,  $S_{\text{odd}} = -0.82 \pm 0.28$ , and  $C_{\text{even}} = -0.21 \pm 0.25$ ,  $C_{\text{odd}} = -0.21 \pm 0.21$ . The difference between  $S_{\text{even}}$  and  $S_{\text{odd}}$  is  $0.65 \pm 0.46$ , less than 1.5 standard deviation from the expected value, zero. We also find that the differences between  $h^0 \rightarrow \gamma\gamma$  and  $h^0 \rightarrow \pi\pi\pi$  modes are less than 0.1 in  $C$  and  $S$ .

The SM corrections due to the sub-leading-order diagrams are different for  $D_{CP+}$  and  $D_{CP-}$  [4]. Therefore, we also perform a fit allowing different  $CP$  asymmetries for  $D_{CP+}$  and  $D_{CP-}$ . We obtain  $S_+ = -0.65 \pm 0.26 \pm 0.06$ ,  $C_+ = -0.33 \pm 0.19 \pm 0.04$ ,  $\rho_+ = 4.5\%$ , and  $S_- = -0.46 \pm 0.45 \pm 0.13$ ,  $C_- = -0.03 \pm 0.28 \pm 0.07$ ,  $\rho_- = -14\%$ .

The dominant systematic uncertainties are from the peaking background and the  $m_{\text{ES}}$  peak shape uncertainties (0.04 in  $S$  and 0.03 in  $C$ ). For the former, we vary the amount of the peaking background according to its estimated uncertainty and vary the  $CP$  asymmetry of the charmless component between  $\pm \sin 2\beta$  of the world-

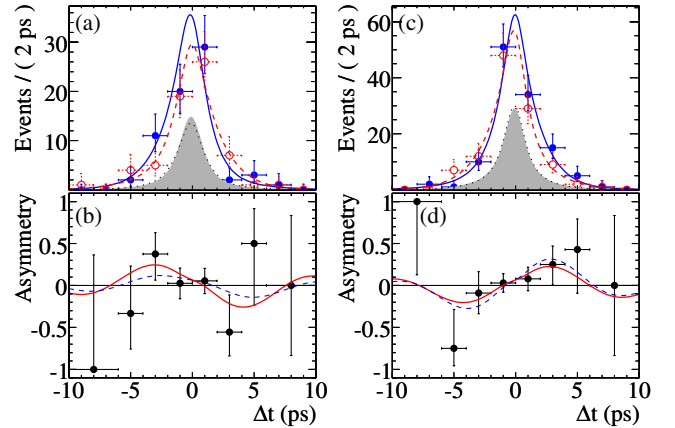


FIG. 2 (color online). The  $\Delta t$  distributions and asymmetries for (a,b)  $CP$ -even and (c,d)  $CP$ -odd events in the signal region ( $m_{\text{ES}} > 5.27 \text{ GeV}/c^2$ ). In (a) and (c), the solid points with error bars and solid curve (open circles with error bars and dashed curve) are  $B^0$ -tagged ( $\bar{B}^0$ -tagged) data points and  $\Delta t$  projection curves. Shaded areas ( $B^0$ -tagged) and the dotted lines ( $\bar{B}^0$ -tagged) are background distributions. In (b) and (d), the solid curve represents the combined fit result, and the dashed curve represents the result of the fits to  $CP$ -even and  $CP$ -odd modes separately.

average value. We study the latter effect using an alternative line shape [20] taking into account a possible non-Gaussian tail in the  $m_{ES}$  distribution. Other systematic uncertainties typically do not exceed 0.01 in  $S$  or  $C$  and come from the following sources: the assumed parameterization of the  $\Delta t$  resolution function; the uncertainties of the peaking background;  $m_{ES}$  width and the combinatorial background threshold function;  $B^0$  lifetime, and mixing frequency; the beam-spot position; and the interference between the CKM-suppressed  $\bar{b} \rightarrow \bar{u}c\bar{d}$  and CKM-favored  $b \rightarrow c\bar{u}d$  amplitudes in some  $B_{tag}$  final states, which gives deviations from the standard time evolution function Eq. (1) [21]. Uncertainties due to the vertex tracker length scale and alignment are negligible. Summing over all systematic uncertainties in quadrature, we obtain 0.05 for  $S$  and 0.04 for  $C$ .

In conclusion, we have measured the time-dependent  $CP$  asymmetry parameters  $S = -0.56 \pm 0.23 \pm 0.05$  and  $C = -0.23 \pm 0.16 \pm 0.04$  from a sample of  $340 \pm 32 B^0 \rightarrow D_{CP}^{(*)} h^0$  signal events. The result is 2.3 standard deviations from the  $CP$ -conserving hypothesis  $S = C = 0$ . The parameters  $S$  and  $C$  are consistent with the SM expectation, i.e., the world average  $-\sin 2\beta = -0.725 \pm 0.037$  [6] and zero, respectively.

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